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FAR-FIELD SOUND PROPAGATION AS RELATED
TO SPACE VEHICLE STATIC FIRINGS

By

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ABSTRACT

As space vehicle boosters become larger in thrust, the emitted sound energy that is propagated through the atmosphere becomes of greater concern to the organizations performing the static firings due to disturbance or nuisance to the near-by communities. Far-field sound intensity levels are calculated using the inverse square law and a theoretical model based on the acoustical equivalence to Snell's refraction law. The theoretical model requires a knowledge of the sound source intensity and the velocity of sound profile. This model requires accurate measurements of the vertical structure of virtual temperature, wind speed and direction from which the velocity of sound profile is derived. The necessary simplifying assumptions used in deriving the theoretical model will be discussed. The sound intensity level as derived from the theoretical model and empirical measurements from an acoustical horn and the static firings of the SATURN booster are compared. Practical operational techniques used in performing atmospheric measurements, atmospheric predictions, and sound intensity level calculations for the static firing of large boosters will be discussed.

SECTION I. INTRODUCTION

A. CHARACTERISTICS OF SOUND SOURCE

In order to obtain an appreciation for the magnitude of the sound generated from several aerospace boosters, a comparison of the estimated total acoustical power level for the JUPITER, SATURN I, SATURN V and NOVA is presented (Fig. 1). These values are determined by assuming an exhaust velocity for the engines and that 1% of the jet's total power is converted into acoustical power. An increase of only 10 for the total acoustical power level for the 1.5 million pound thrust engine over that of the 0.15 million pound thrust engine is not an impressive increase in acoustical power level. However, of greater importance is that as the engine thrust increases a larger portion of the acoustical energy is generated at the lower frequencies. The theoretically derived power levels do not form an estimate of the frequency dependence of the acoustical energy. For this reason experimental values for the acoustical power level are needed. It has already been learned (Ref. 7) that the power spectra of peak acoustical energy shifts by one octave toward lower frequencies for the JUPITER engine to that of the SATURN I. The acoustical energy generated by the SATURN I engine peaks between 10 cps and 100 cps (Ref. 7). In terms of sound propagation through the atmosphere, the lower the frequency the smaller is the acoustical attenuation and thus the greater possibility of disturbances to the surrounding communities. Also, the lower the frequencies the higher the probability becomes that building structures will be damaged due to acoustical energy coming in resonance with the natural frequencies of building structures.

B. INVERSE SQUARE LAW FOR SOUND PROPAGATION

Using the estimated total acoustical power level for the several vehicles and the assumptions of the inverse square law for sound propagation, the over-all sound pressure level in decibels (db re: 10^{-13} watts) versus distance from the sound source is calculated (Fig. 2). The value of 110 db has been selected as a critical over-all sound pressure level in terms of disturbances to the surrounding community. The radius for the critical sound pressure level for the SATURN I, assuming the inverse square law, is 10 km (6 miles) and for the SATURN V the radius is 19 km (13 miles). Under the assumptions of the inverse square law for sound propagation, one would predict that every time a SATURN V was static fired at George C. Marshall Space Flight Center, (MSFC), an over-all sound pressure level $\geq$ 110 db would result over the city of Huntsville, as well as a number of surrounding communities (a populated area of approximately 150,000 inhabitants) (Fig. 3).

It will be recalled that the inverse square law assumes a homogeneous media through which the acoustical energy is propagated, i.e., the velocity of sound with respect to altitude and horizontal distance is everywhere constant. We know this condition never exists in the real atmosphere. Even so, the inverse square law has some theoretical value in understanding certain boundary or limiting conditions for the propagation of sound through the atmosphere.

C. APPROACHES TO THE PROBLEM OF FAR-FIELD ACOUSTICS

In view of the estimated over-all sound pressure level versus distance from the sound source by the inverse square law, the question is asked: "What is being done at MSFC to eliminate the problem of sound generated by the SATURN engines?" Three approaches are being followed namely: (1) Develop a new static test facility located in a less densely populated area. This is being done. Plans call for an operational facility at the Mississippi Test Operations (MTO) located in southern Mississippi by early 1966. The MTO will static test the SATURN V booster and larger boosters yet to be developed. The first group of SATURN V boosters will, however, be static tested at MSFC. (2) Invest in an engineering effort to suppress the sound at the source. This is being done. The Test Laboratory already has a working sound suppression model. From this model sound suppression techniques can be studied, and the feasibility of engineering a full-scale facility to suppress the sound from the SATURN V and larger boosters can be determined. (3) The third approach is to (a) determine the relationship between atmospheric conditions and anomalous sound propagation and (b) predict the atmospheric conditions which cause anomalous sound propagation and (c) restrict static tests to those conditions which will not produce high sound pressure levels in the surrounding communities. This area of analytical investigations and practical operational procedures will be pursued in the discussions of this paper.

SECTION II. RAY ACOUSTICS AND SOUND INTENSITY LEVEL

A. RAY ACOUSTICS

One method that has been used by several investigators (Refs. 5, 8, 10, 12 and 13) to study the relationship between atmospheric conditions and anomalous sound propagation over long distances is known as ray acoustics or sound ray tracing technique. Essentially, the acoustical equivalence to Snell's refraction law is derived and a system of practical equations developed to obtain the ray patterns. "By definition a ray is a curve whose tangent everywhere points into the direction in which the energy contained in the vibrating element is propagated" (Heybey, Ref. 9). The derivation of the acoustical equivalence to Snell's refraction law will not be presented in this paper, since the derivation in view of the applications to the acoustic problem at MSFC is presented in detail in the two excellent works of Heybey (Refs. 8 and 9). Furthermore, Heybey derives the necessary analytical expressions to determine the theoretical sound intensity level (Ref. 8).

B. The first essential in applying the sound ray tracing technique and the determination of sound intensity level is the velocity of sound profile. The velocity of sound is given by:

$$V = 20.0468\sqrt{T^*} + \text{Wind Component}$$

where T^* is virtual temperature in °K. The wind component is longitudinal to the azimuth of interest and is determined from the wind speed and direction. V is the velocity of sound in m/sec.

Virtual temperature and wind component are either measured values or predicted values with respect to height above the local terrain.

The system of practical equations to map the rays as they transverse the atmosphere has been devised by several investigators (Refs. 5, 8, 10, 12, 13 and 20). The development of the practical ray tracing equations that are used in the investigations for this paper is due to Mr. J. Mabry, a member of the Aero-Astrodynamics Laboratory (Ref. 12).

The velocity of sound with respect to height is considered to be linear over a small height increment or layer. The height increment is taken to be approximately 200 m as determined by data reduction for the velocity of sound from rawinsonde measurements at one-half minute increments of balloon elapse time (Ref. 4). The velocity of sound with respect to altitude is the only required data for the ray tracing equations. This system of equations simply traces the ray through the atmosphere by computing the segment of path in each succeeding layer. The path of the ray will either continue to transverse the layers or return back to the earth's surface, depending on the slopes of the velocity of sound profile or vertical gradients.

From ray acoustic calculations the vertical gradients of the velocity of sound with respect to the ray patterns can be characterized. Five idealized velocity of sound profiles are presented in Fig. 4. The first profile has a single negative gradient. The rays are deflected upward into the atmosphere, and this produces the condition of no rays returning. The second profile is known as the "zero" gradient. This condition is required for the inverse square law of sound propagation to be valid. The third profile has a positive gradient followed by a negative gradient. This condition produces ray concentration. In practice this condition has been observed to produce near uniformity in the distance between consecutive intercepts of the ray to the plane tangent to the initial velocity of sound. So an alternate description for this condition could be "uniform rays returning".

The fourth condition is that velocity of sound profile which produces ray focusing. It is characterized by a negative gradient, then a positive gradient, followed by a negative gradient. The positive gradient must be such that the velocity of sound in this layer exceeds that at the earth's surface or initial velocity of sound.

The fifth profile produces the combination condition of ray concentration and focusing.

The actual performance of the task of computing the path of the ray is lengthy and can best be performed through the use of an electronic computer. Two types of computers may be used: one, an analog computer, and secondly a digital computer. Figures 4, 5 and 6 present three different ray patterns. These evaluations were performed by the Computation Laboratory (Ref. 21) using a general purpose analog computer assigned to the Aero-Astrodynamics Laboratory. Should these ray patterns appear similar to those of Perkins (Ref. 10), the similarity is not coincidental. The velocity of sound profiles were so selected to check out the computer program. The purpose of the analog computer program for the ray acoustic at MSFC is for basic research and to simulate the ray patterns from a moving sound source as would be experienced from the flight of a space vehicle.

Ray acoustics calculations can be performed by a digital computer and the results tabulated for further analysis or presented in graphical form. For static test operations at MSFC, the Test Laboratory performs this operation. An example of a ray plot is given in Fig. 8.

SECTION III. THEORETICAL SOUND INTENSITY LEVEL

The ray patterns in themselves do not give an estimate of the sound intensity level to be expected from a given velocity of sound profile. Only through experience and the collection of measured sound pressure level data can a correlation between the ray patterns and sound intensity level be obtained. However, from theoretical consideration, it can be stated that in those areas where sound rays do return the sound intensity level may be higher than that predicted by the inverse square law, and in a focal area the sound intensity level may be much higher than that predicted by the inverse square law. Conversely, in those areas where no rays return the sound intensity level will be lower than that predicted by the inverse square law.

Estimates of the sound intensity level versus distance from the static test of an aerospace vehicle that has never been static fired, for the condition of no rays returning, rays returning and ray focusing must be made for operational planning.

Due to a method derived by Heybey (Ref. 8) the sound intensity level can be estimated from a knowledge of the velocity of sound profile and the acoustical power level of the sound source. A similar method is presented in the Handbook of Aerophysics (Ref. 20). Since there are no derivations presented in reference 20 and the article is difficult to follow, we shall use the equations derived by Heybey.

The sound intensity level, IL, is calculated from the expression:

$$IL = D + 10 \log \frac{1}{2\pi} + 10 \log \left[\frac{1}{X_s} \frac{1}{\left| \frac{dX_s}{d\theta_o} \right|} \operatorname{ctn} \theta_0 \right]$$

where D is derived from the total power level, PWL, at the sound source. X_s is the horizontal distance from the sound source to the incidence of the ray landing on the plane tangent to the earth's surface at the sound source. X_s and $\frac{dX_s}{d\theta_o}$ are derived from the velocity of sound profile. θ_0 is the angle of the ray leaving the sound source and is incremented at small arbitrary intervals. IL is the over-all sound intensity level in the units, db re: 10^{-13} watts/ft^2.

The characteristics of this equation are:

(1) When the increase of the velocity of sound with respect to height is linear, the argument of the logarithm for small θ_0 angles is approximately $\frac{1}{X_s^2}$. Therefore, under this condition the inverse square law for sound propagation is approximated.

(2) At a focal point the intensity level is undefined since at a focal point $\frac{dX_s}{d\theta_o}$ is zero. (The condition of $\frac{dX_s}{d\theta_o} = 0$ defines a focal point.)

(3) When the velocity of sound decreases at all altitudes, no rays return and hence the intensity level is not determinable. Only for the condition of rays returning can the intensity level be calculated.

In deriving the intensity level equation as well as the practical ray acoustic equation, it is necessary to make certain simplifying assumptions about the structure of the atmosphere. These assumptions are:

(1) That the velocity of sound with respect to altitude is linear over small altitude intervals.

(2) That the velocity of sound is uniform with respect to horizontal distances for the linear altitude intervals.

(3) That there is no vertical wind component.

(4) That there is no horizontal acceleration in the wind velocity field.

In deriving the intensity level equation attenuation of energy is not taken into account. It is hoped through the continued acoustic and atmospheric measuring programs at MSFC that an appropriate empirical attenuation term can be determined.

In spite of these limitations useful and practical results can be obtained from the sound intensity level equation. In Fig. 9 a comparison is made between the theoretical sound intensity level, inverse square law, and measured over-all sound pressure level for a static test of SATURN I, which was conducted on February 27, 1963, 2248 Z (1648 CST). The sharp rise in the sound intensity level curve at 16 km distance is attributed to a focal condition.

Since at a focal point the IL is not analytically defined, the calculated IL is unrealistically high due to the practice of using a finite increment of θ_0 (the angle at which the ray parts from the sound source). Some form of space averaging should be devised to represent the IL for the focal zones. Also, it is considered that the IL may be reduced at a focal point by ray interference (Ref. 20). Moreover, the IL as shown in Fig. 11 is with respect to a flat earth's surface. Terrain features which intercept the incoming rays may change the IL pattern to some extent, particularly for small θ_0. More serious than this feature is the lack of an appropriate attenuation term, particularly for large distances, i. e., distances greater than 15 km.

At 30 and 34 km distances from the sound source two other focal points are in evidence. These focal points are also apparent from the ray trace given in Fig. 8.

Another way to present the sound intensity levels derived from the rawinsonde measurements for the velocity of sound and the acoustical power of the sound source is shown in Fig. 11. Here the sound intensity levels were derived for approximately 36 azimuths and isacoustic lines (lines of constant sound intensity level) have been drawn. The sound source is considered to be at the center of the coordinate axis. In those areas where rays do not return the sound intensity levels are not derived. (Fig. 10 is to be used an an overlay for Fig. 11 and Figs. 16-19.)

From Fig. 11 several focal areas are in evidence. The focal areas are characterized by high intensity level values and large gradients.

Due to the lack of better information on attenuation of sound, the mean values of excess attenuation by Wilhold (Ref. 19) will be used to illustrate how the theoretically derived sound intensity levels of Fig. 11, may be reduced by using these for excess attenuation. Given, for example, the IL at 15 km is 120 db, then using the attenuation factor which is a function of the octave center band frequency, the sound pressure level for the given frequencies at 15 km can be estimated.

Table 1

Center Band Frequency (cps)	Excess Attenuation (db/km)	Theoretical Intensity Level = 120 db (120 db less Excess Attenuation)
10	0.148	118
20	0.360	115
40	0.690	110
80	1.15	103
160	1.70	94
320	2.40	84
640	3.30	70
1280	3.90	61

With the addition of the attenuation factor, the IL as given in Fig. 11 becomes more reasonable with physical reality except in the focal areas.

It is known that the sound generated by the static test of space engines has directivity due to the flame deflectors (Ref. 16). So an expression giving the sound intensity as function of distance from the sound source and sound vibration frequency should be of the form:

IL = F (PWL of Source) + F (Directivity of Source) + F (Frequency of Source) + F (Velocity of Sound in the Propagating Media) +F(Attenuation).

The first term, the PWL of source, can be determined theoretically, but it should also be determined from measurements for the particular engine or engine cluster. The second term, directivity of source, is dependent on the configuration of the static test stand and engine characteristics and should be determined from measurements. The third term, frequency of sound source, should be determined from measurement. The fourth term, velocity of sound in the propagating media, is controlled by the atmospheric conditions and it is suggested that the ray acoustics and theoretical sound intensity level procedures devised by Heybey and Mabry (Refs. 9 and 12) is a good point of departure for further research. The fifth term, the attenuation of sound through the atmosphere, is probably the least understood and is an area for considerable basic research using carefully controlled sound and atmospheric measurements. The attenuation term should include molecular and classical attenuation as well as dynamic effects or atmospheric turbulence.

SECTION IV. ATMOSPHERIC AND ACOUSTIC MEASURING PROGRAM AT MISSISSIPPI TEST OPERATIONS

There is in addition to the existing atmospheric and acoustic measuring program at MSFC - Huntsville, a combined effort on the part of Aero-Astrodynamics Laboratory and Test Laboratory to obtain simultaneous atmospheric measurements and acoustical measurements at Mississippi Test Operations (MTO). The Test Laboratory uses an exponential acoustical horn as the sound source (Ref. 15). At MTO the horn has a sound power level capability up to 6,000 watts.

(AT MSFC the sound power level capability of the acoustical horn is up to 178,000 watts). The sound pressure is measured by sound pressure level meters and tape recording type sound pressure instruments. The atmospheric measurements are obtained from the rawinsonde GMD-1B system. Using these simultaneous measurements of sound pressure levels and atmospheric measurements from which sound intensity levels have been calculated, a comparison is made between the sound intensity level and sound pressure level. The exact position at which the sound pressure level measurements were made was not communicated to the author (Ref. 22). Therefore, the best agreement between the sound pressure level and the theoretical sound intensity level within ± 500 m distance was chosen for this comparison. These data are summarized in Figs. 12 and 13 for two different atmospheric conditions. In Fig. 12 a comparison is made between sound intensity level and the measured sound pressure level for the atmospheric conditions which produce uniform rays returning. The standard regression error is 5.2 db. In Fig. 12 the intensity level for all conditions of rays returning, including focal conditions are compared with the sound pressure level measurements. The standard regression error here is 7.1 db. Contributing to the regression errors are: (1) Theoretical assumptions for the intensity level calculations (2) errors in atmospheric and acoustic measurements and (3) time and space variability of atmospheric parameters. The major criticism of this comparison lies in the manner in which the best agreement between the sound intensity level and the sound pressure level measurements was selected. In view of the influence of small errors in the velocity of sound profile on the sound intensity level and short time variations in the wind flow, the comparison made in this manner may not be entirely invalid. Plots were made of the difference between the sound pressure level and the sound intensity level versus distance from the sound source, and no apparent correlation with respect to distances from sound source was noted. Therefore, it is concluded that under similar situations at MTO usable and practical results from the sound intensity level calculations can be used to predict the expected sound pressure level versus distance from source for the SATURN V and larger class vehicle boosters.

SECTION V. STATISTICAL ANALYSIS OF SOUND INTENSITY LEVEL

Far in advance of actual static tests, sometimes several years in advance, the planning engineers must know the influence of pertinent atmospheric conditions on the facility operations. Two approaches may be used to show the relationship between atmospheric parameters and engineering design parameters used in planning a facility. One approach is to take the summarized statistics of atmospheric parameters and attempt to derive the influence of these parameters on the facility. The monthly mean values of temperature, wind components and their standard deviations for discrete altitude levels were used, by Bolt Beranek and Newman N (Ref. 23) to arrive at an estimated frequency at which sound generated from the vehicle would be intensified by quadrant areas. Estimates based on such a procedure should be viewed with caution because the correlations between parameters with respect to altitude should be considered. Often times the required correlation values are not immediately available and must be derived.

It is proposed that a better procedure is to (1) derive the required analytical equations relating the atmospheric variables to that of the required engineering design parameters, (2) use the individual atmospheric measurements to calculate the engineering parameters for design and (3) summarize these data in a statistical manner.

This method will not only yield a more efficient estimate of the frequency of the occurrence for the particular parameters of interest, but will often times be more economical than computing all of the required correlations between the atmospheric parameters themselves.

This procedure was followed in constructing Figs. 14 through 19 which will be discussed in the following paragraphs. Using the individual rawinsonde measurements taken at MSFC at 1630 CST for January 1962 and January 1963, the ray acoustics and intensity levels were calculated. The frequency at which the rays return along each of 36 azimuths was computed. From Fig. 14 it can be seen that 100% of the 1630 CST rawinsonde measurements produced rays returning somewhere along the 90° azimuth (east of MSFC). Along the west azimuth 270° only 35% of the 1630 CST rawinsonde measurements produced rays returning. Similarly, the frequency of rays returning along the azimuths 90° and 270° for July (Fig. 15) are 60% and 18% respectively. Any time rays returned, the sound pressure level from a static test can be expected to be higher than those conditions with no rays returning. Therefore, charts like these for all months of the year would assist a site planning group to take optimum advantage of test facility and community populations in orientating the static test stand such that there is a minimum likelihood for disturbances due to anomalous sound propagation resulting from test operations. From a knowledge of the prevailing wind direction up to 3,000 m altitude over Huntsville these conclusions could have been drawn: the frequency at which rays returned would be higher toward the east than toward the west. However, the relative frequency for rays returning for the two directions could not be stated. An advantage of this information has already been used by the Facility Planning Group at MSFC in the design and layout of the SATURN V static test stand.

A knowledge of the frequency of rays returning anywhere along an azimuth leaves much to be desired for detail facility planning. More useful would be a knowledge of the frequency of rays returning within a given area. Since the computations of rays returning were by necessity carried out in a polar coordinate system a unit area is designed by 5 km intervals along each of the 36 azimuths and ±5° along each of the 36 azimuths. The frequencies at which at least one ray returned within a

5 km interval along each of the 36 azimuths were computed. These frequencies are summarized for January and July (Figs. 16 and 17). The highest insistence of rays returning is east of the static test stand out to a distance of 10 km. It is noted that the Army Office Buildings and Industrial Operations are located in the first 5 km of the static test stand. Between 10 and 20 km east of the test stand is located a recently constructed residential area. The business district of Huntsville is located northeast of the static test stand between 10 and 15 km. So, it is obvious an engineering effort should be made to minimize the sound pressure level produced by the boosters in these directions. During July the frequency of rays returning versus distance from source is more circular than for January. The boundaries of the Federal Reservation are approximated by a circle of 10 km radius. Thus, it is observed that there is less than a 25% chance that rays will return outside the reservation boundaries during July.

Due to the directivity effects the static test stand should be orientated such that the sound pressure level is minimized east and northeast of the static test stand. These conclusions are valid for the existing community construction. However, it is now understood that a multi-million dollar jet airport will be constructed just west of the arsenal boundaries in 1965 or 1966. This poses another problem and that is predicting the future growth of a community surrounding the static test area.

The question that still must be answered is how frequent will atmospheric conditions be such that anomalous sound propagation will cause distrubances to the outlying community due to static test of the SATURN V or other vehicles yet to be built. Using the theoretical intensity level equation as described previously, the frequencies at which the intensity levels equal or exceed 110 db for those cases which produce rays returning have been calculated. It must be realized that no attenuation factor has been included in these calculations; therefore, the frequencies at which the intensity level exceeds 110 db will be higher than they should be. If the vibrating frequencies of the sound spectrum for the SATURN V is somewhat lower than the SATURN I, the neglect of the attenuation terms may not appreciably change the frequency at which 110 db is exceeded versus distance from the sound source. From Figs. 18 and 19 it is concluded that when rays return there is a high probability that the sound generated by the SATURN-V will equal or exceed 110 db out to distances of 20 km.

As a final note on the statistical analysis as presented in this paper, it is realized that the available data sample is small for the detailed statistical treatment as presented in Figs. 16 through 19. The techniques or methods of statistical analysis should prove helpful in determining statistics of acoustical parameters for other locations and related problems. However, the statistical analysis of the acoustical parameters should be performed using individual atmospheric measurements specifically for the localities of interest.

SECTION VI. OPERATIONS

At MSFC an atmospheric measuring system has been in operation since October 1961. The equipment consists of two GMD-1B's with capabilities of operating as GMD-2 units. Through a switching mechanism the GMD-2 capability can be operated automatically to produce punched cards for azimuth and elevation angles, ratios of temperature and humidity ordinates, and slant range at 5-sec intervals of balloon flight time. This later system is known as the ADP-System, that is, automatic data processing system (Ref. 24). The atmospheric measurements at MSFC are the responsibility of the Atmospheric Measuring Group which is under the direction of Mr. Robert Turner. Predictions up to 36 hr in advance of static tests are required for the wind speed, direction and virtual temperature profiles. Weather charts by facsimile and weather teletype information are received to assist in making these predictions. From 6 hr prior to static test time until actual static test time, rawinsonde measurements are performed at 1 to 2-hr intervals. Also, during this time the Test Laboratory obtains sound pressure level measurements using the acoustical horn as a sound source. If through these measuring techniques and predictions the sound pressure level appears to be too high, that is, equal to or greater than 110 db in the community, the test conductor cancels the static firing and reschedules the test when the atmospheric conditions are more favorable.

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REFERENCES

1. Benson, R. W. and H. B. Karplus, "Sound Propagations Near the Earth's Surface as Influenced by Weather Conditions," WADC Technical Report 57-353, Part I ASTIA Document No. AD130793, March 1958.
2. Bruns, R. H. and L. F. Keene, "Saturn Sound Focusing Prediction at LOC," MTP-LVO-63-5, May 1963.
3. Burkhard, M. D., H. B. Karplus and H. J. Sabine, "Sound Propagation Near the Earth's Surface as Influenced by Weather Conditions," WADC Technical Report 57-353, Part II, December 1960.
4. Case, Bettye A., "Computer Evaluation of Rawinsonde Observations," MTP-AERO-63-6 (Supersedes MTP-AERO-62-41), January 1963.
5. Cox, E. F., H. J. Plagge and J. W. Reed, "Meteorology Directs Where Blast Will Strike," Bulletin AMS, Vol. 35, No. 3, March 1954.
6. Dorman, W. J. and J. A. Brown, "Meteorological Focusing of Sound and Blast Waves and Its Prediction by Analogue Techniques," BRL Report No. 1014, April 1957.
7. Dorland, W. D., "Far-Field Noise Characteristics of Saturn Static Tests," NASA TN D-611, August 1961.
8. Heybey, W. H., "Notes on Sound Propagation and Focusing," MTP-AERO-62-17, March 1962.

REFERENCES (CONT.)

9. Heybey, W. H., "Theoretical Aspects of Planar Sound Propagation in the Atmosphere," MTP-AERO-62-72, October 1962.

10. Perkins, Beauregard, Jr., P. H. Lorrain and W. H. Townsend, "Forecasting the Focus of Air Blasts Due to Meteorological Conditions in the Lower Atmosphere," BRL Report No. 1118, October 1960.

11. Mabry, J. E., "Dependence of the Acoustical Focus Location on Meteorological Conditions in the Two-Layered Atmosphere," MTP-AERO-62-60, July 1962.

12. Mabry, J. E., "Numerical Method for Acoustical Focal Point Determination in a Multi-Layered Atmosphere," MTP-AERO-60-20, March 1962.

13. Rothwell, P., "Calculation of Sound Rays in the Atmosphere," Journal of the Acoustical Society of America, Vol. 1, No. 1, Janury 1947.

14. Tedrick, R. N., and R. C. Polly, "A Preliminary Investigation of the Measured Atmospheric Effects Upon Sound Propagation," MTP-TEST-63-6, May 1963.

15. Tedrick, R. N., "Performance Characteristic of a Large Free-Field Exponential Horn," MTP-TEST-63-4, March 1963.

16. Tedrick, R. N., "Acoustic Focal Zones Around Saturn Static Tests," MTP-TEST-MC-61-21, December 1961.

REFERENCES (CONT.)

17. Turner, R. E. and R. R. Schow, "MSFC Atmospheric Sounding Station Semiannual Operation Review," MTP-AERO-62-59, July 1962.

18. Wiener, Francis M., "Rocket Noise of Large Space Vehicles," Published as a contribution by the Fourth International Congress on Acoustics, Congress Report II, Copenhagen, August 1962.

19. Wilhold, G. A., S. H. Guest and J. H. Jones, "A Technique for Predicting Far-Field Acoustic Environments Due to a Moving Rocket Sound Source," NASA TN D-1832, August 1963.

20. Handbook of Geophysics, Revised Edition, USAFCRL, MacMillan Co., New York, 1961.

21. Barnes, B. B., "Air-Blast Simulation Using High-Speed Repetitive Analog Components, Digital Logic-Control Devices," MSFC Internal Note IN-M-COMP-S-63-2, March 15, 1963.

22. Polly, R. and R. Tedrick, "Far-Field Acoustic Propagation Characteristics at the Mississippi Test Facility," Various Internal Note, Test Laboratory, NASA-Marshall Space Flight Center, Huntsville, Ala.

23. "Acoustical Considerations in the Planning and Operation of Launching and Static Test Facilities for Large Space Vehicles Phase I," Final Report, Contract NAS8-2403, Bolt Beranek and Newman, Inc., December 11, 1961.

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24. Turner, R. E.,* and J. H. Stoudenmire,** "Automatic Radiosonde Data Processing System," Submitted to AMS for publication, February 14, 1964.

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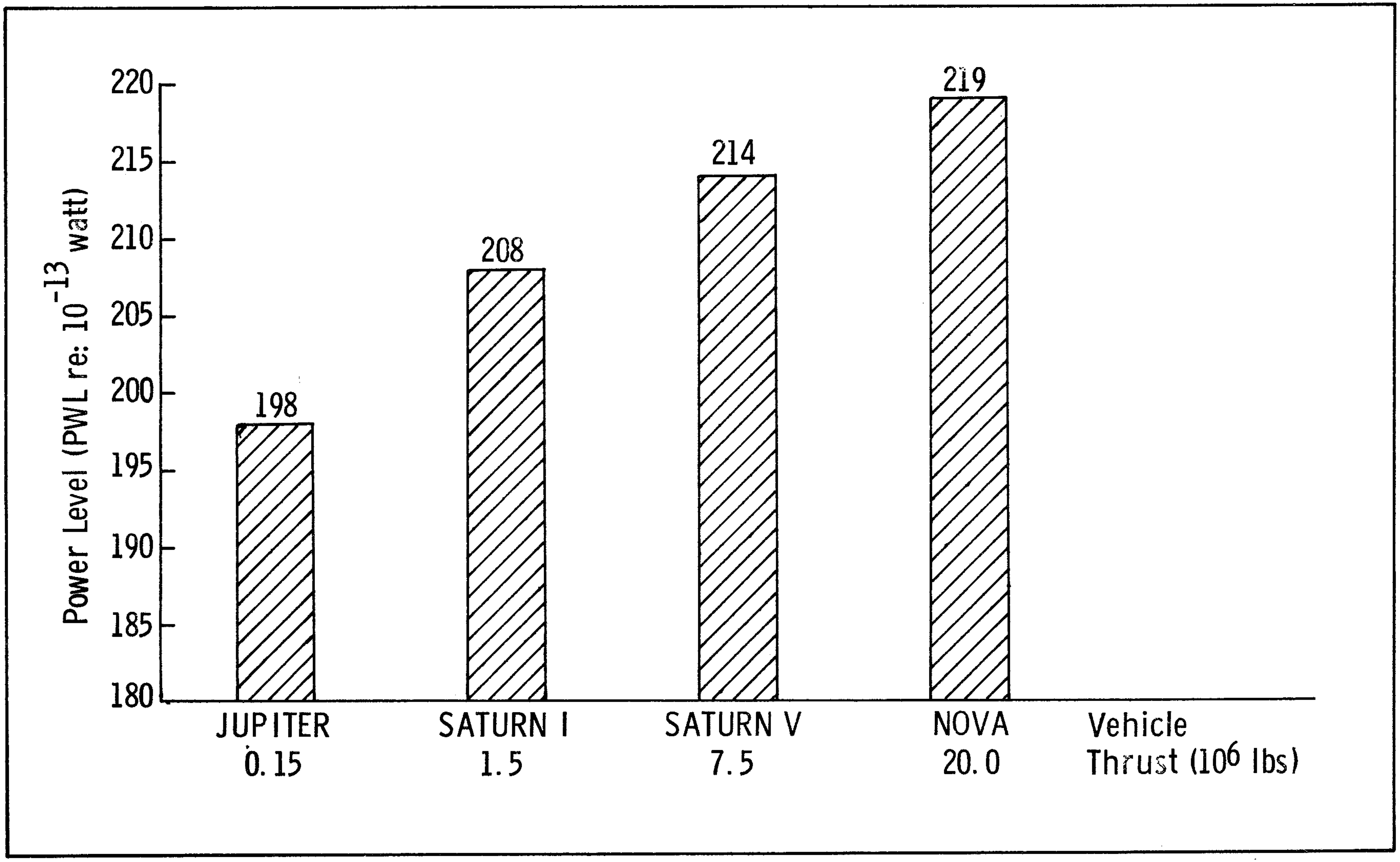


FIG. 1. ESTIMATED ACOUSTICAL POWER LEVEL FOR SEVERAL AEROSPACE VEHICLES

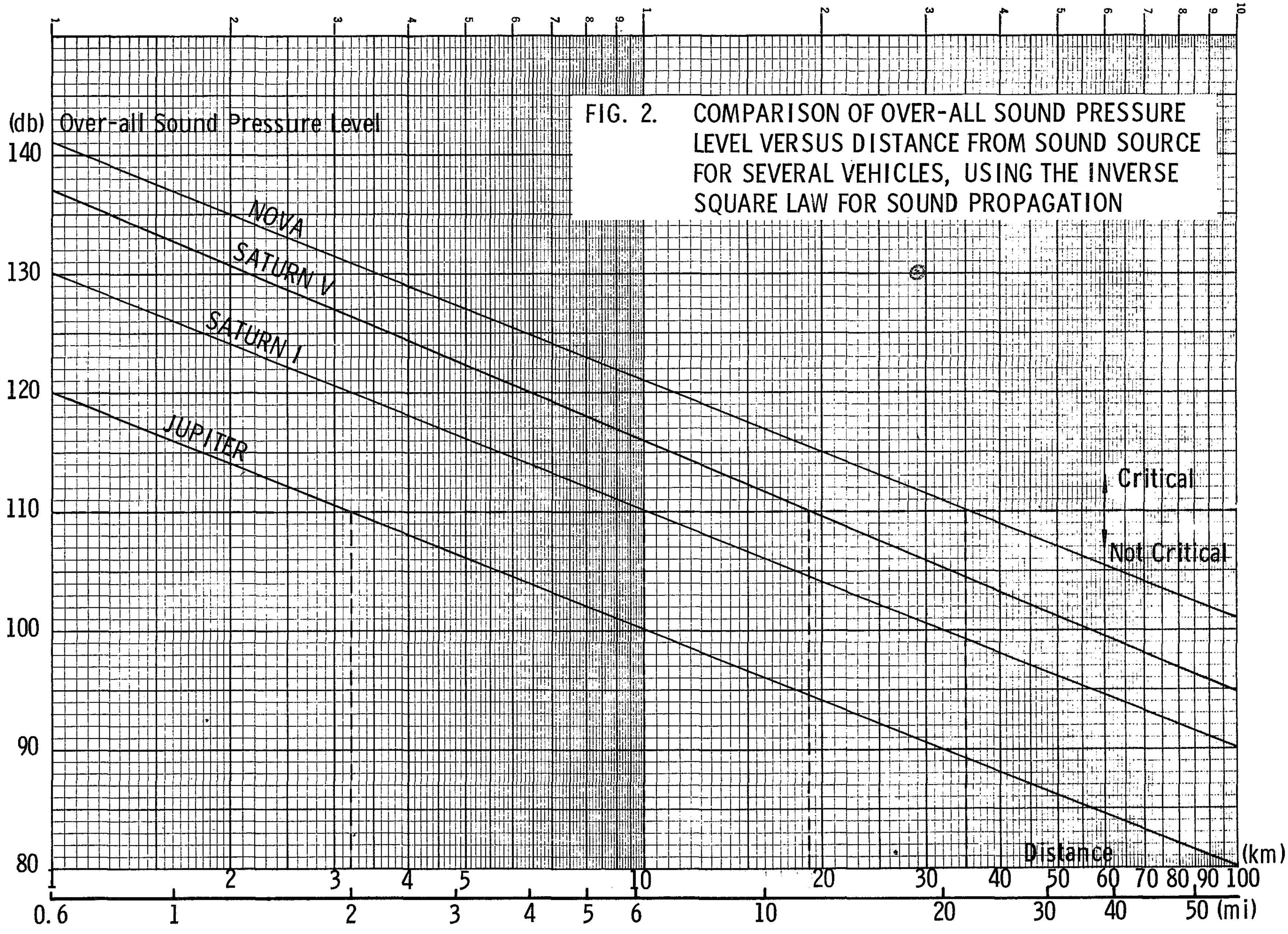


FIG. 2. COMPARISON OF OVER-ALL SOUND PRESSURE LEVEL VERSUS DISTANCE FROM SOUND SOURCE FOR SEVERAL VEHICLES, USING THE INVERSE SQUARE LAW FOR SOUND PROPAGATION

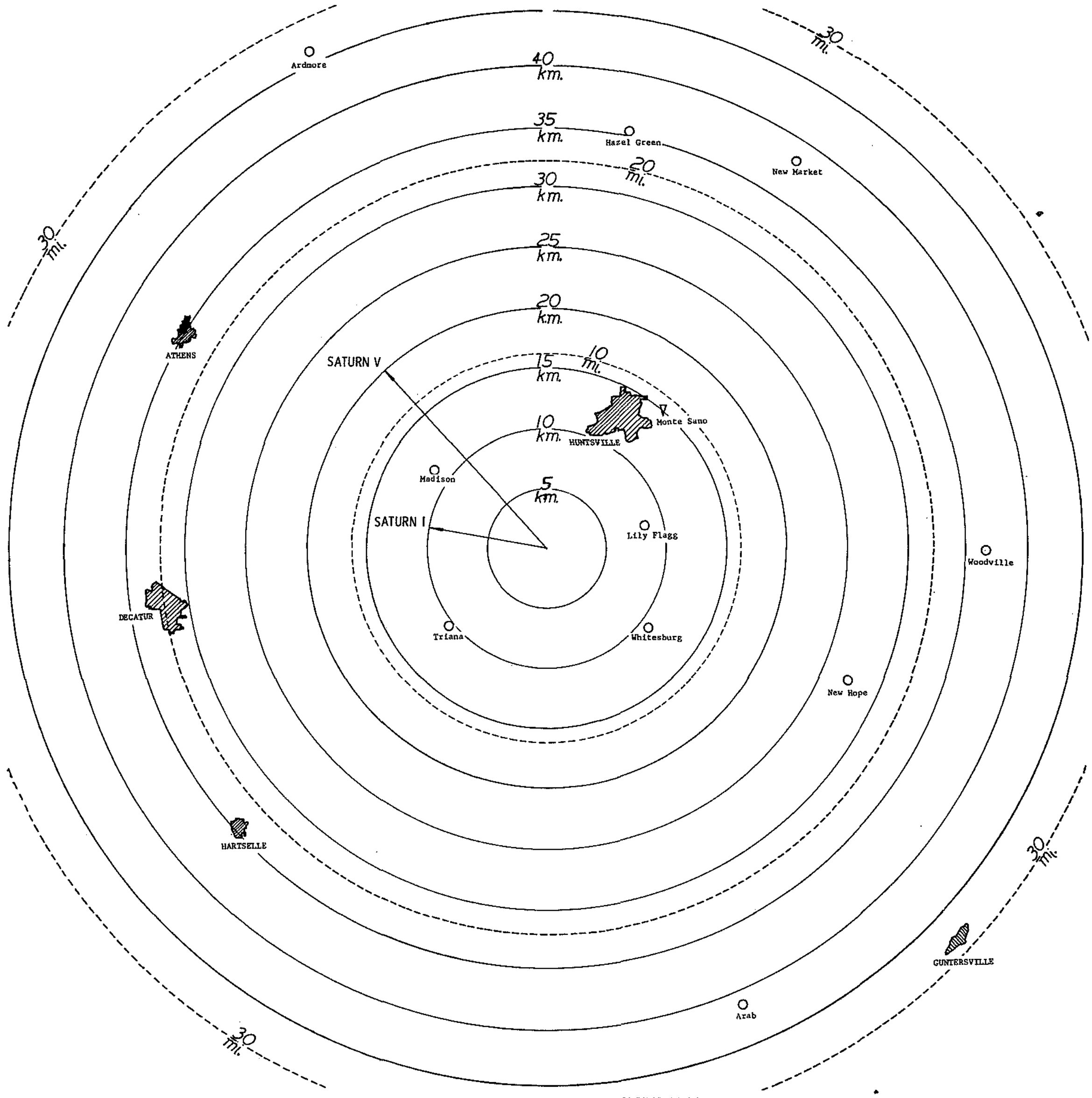
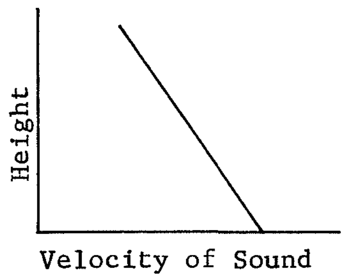


FIG. 3. RADII TO CRITICAL SOUND PRESSURE LEVEL (110 db) FOR SATURN I AND SATURN V USING INVERSE SQUARE LAW

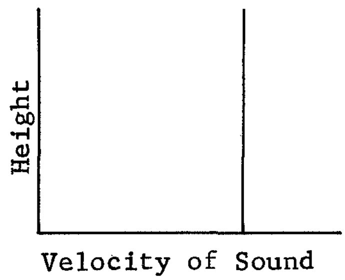
Fig. 4. Idealized Velocity of Sound Profiles and Ray Patterns

1.



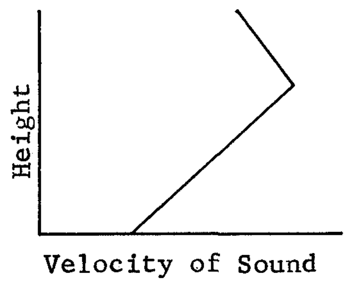
Rays are deflected upward (no rays returning)

2.



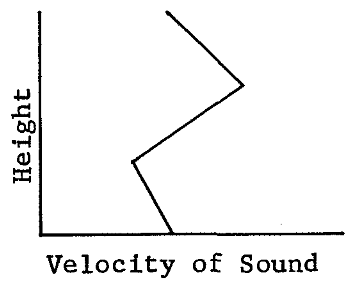
Rays returning uniformly in all directions (Inverse Square Law Condition)

3.



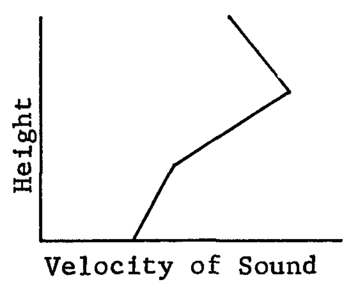
Uniform rays returning (ray concentration)

4.

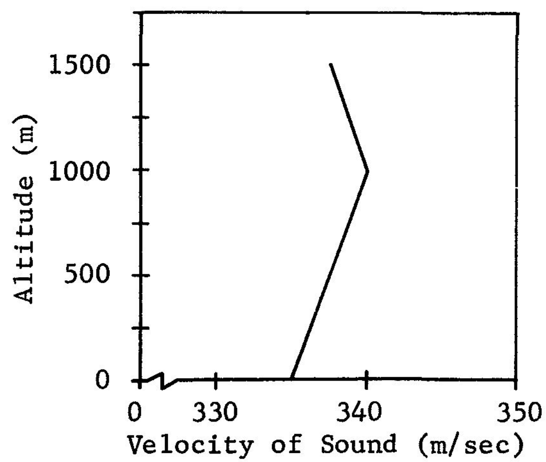


Ray focusing condition

5.



Ray concentration and focusing



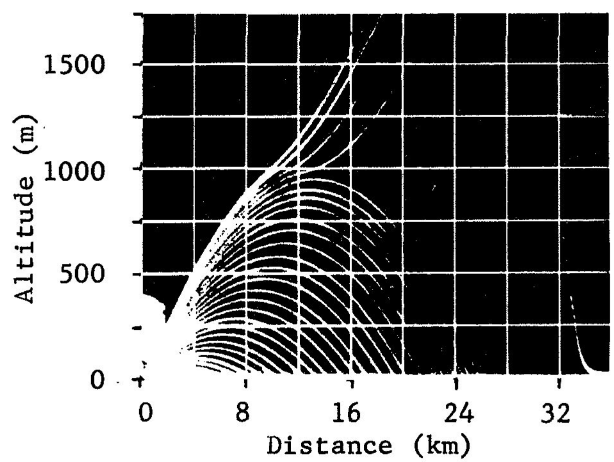


Fig. 5. Analog Computer Evaluation of an Idealized Velocity of Sound Profile Producing Ray Concentration

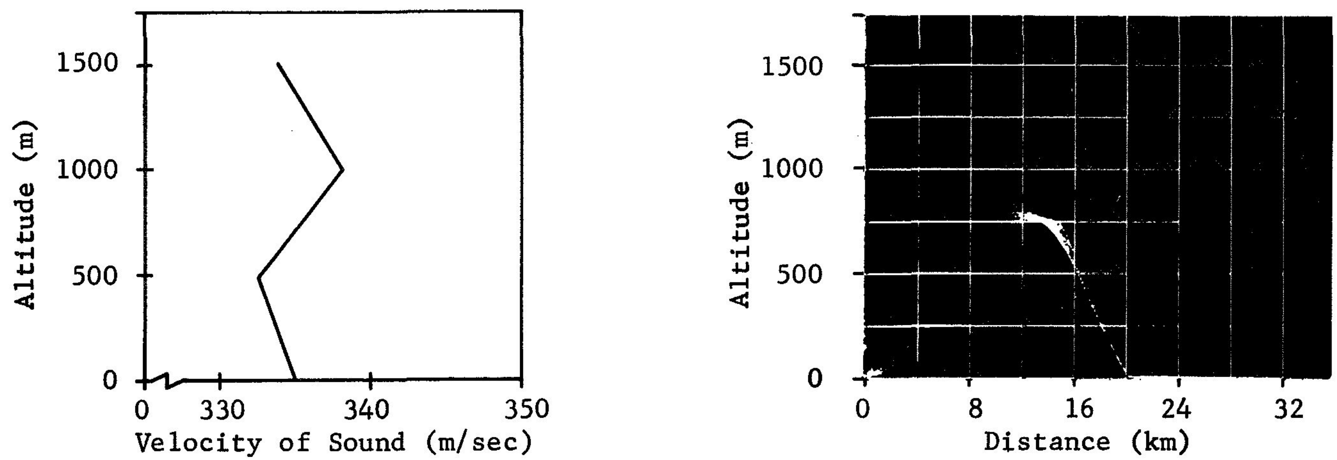


Fig. 6. Analog Computer Evaluation of an Idealized Velocity of Sound Profile Producing Ray Focusing

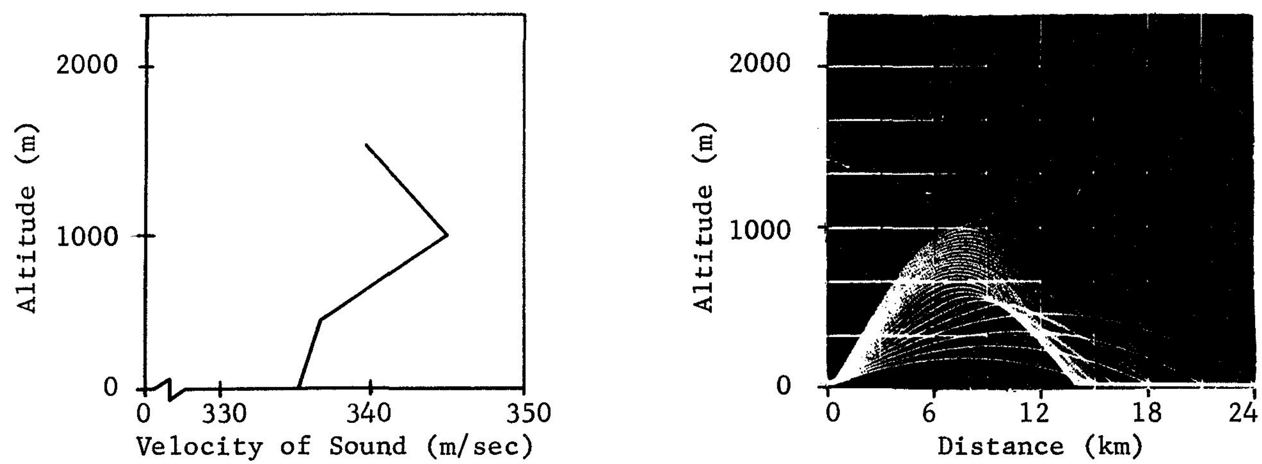


Fig. 7. Analog Computer Evaluation of an Idealized Velocity of Sound Profile Producing Ray Concentration and Focusing

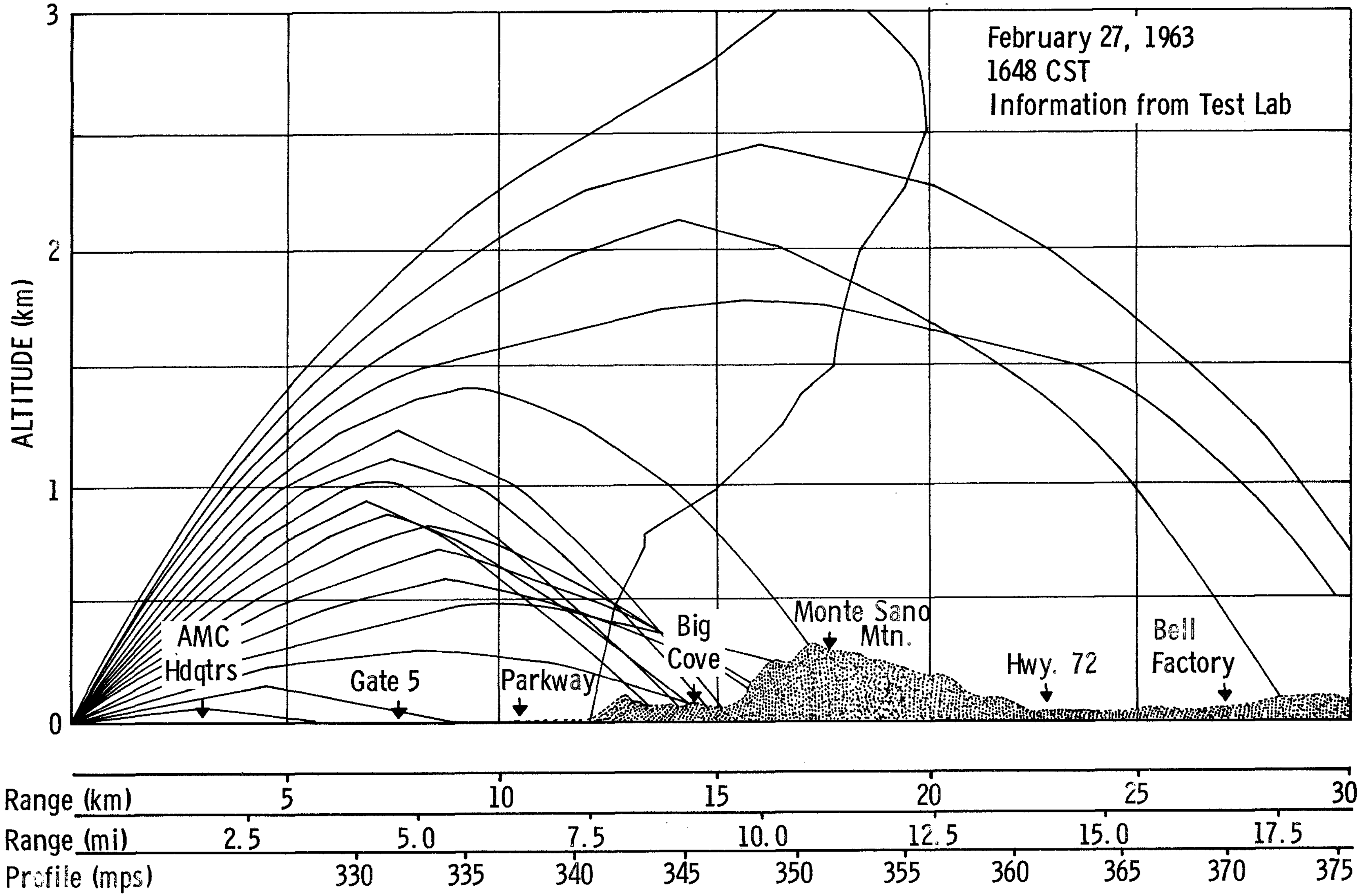


FIG. 8. CALCULATED ACOUSTIC RAY PATHS
HUNTSVILLE, ALABAMA, 45 deg AZIMUTH

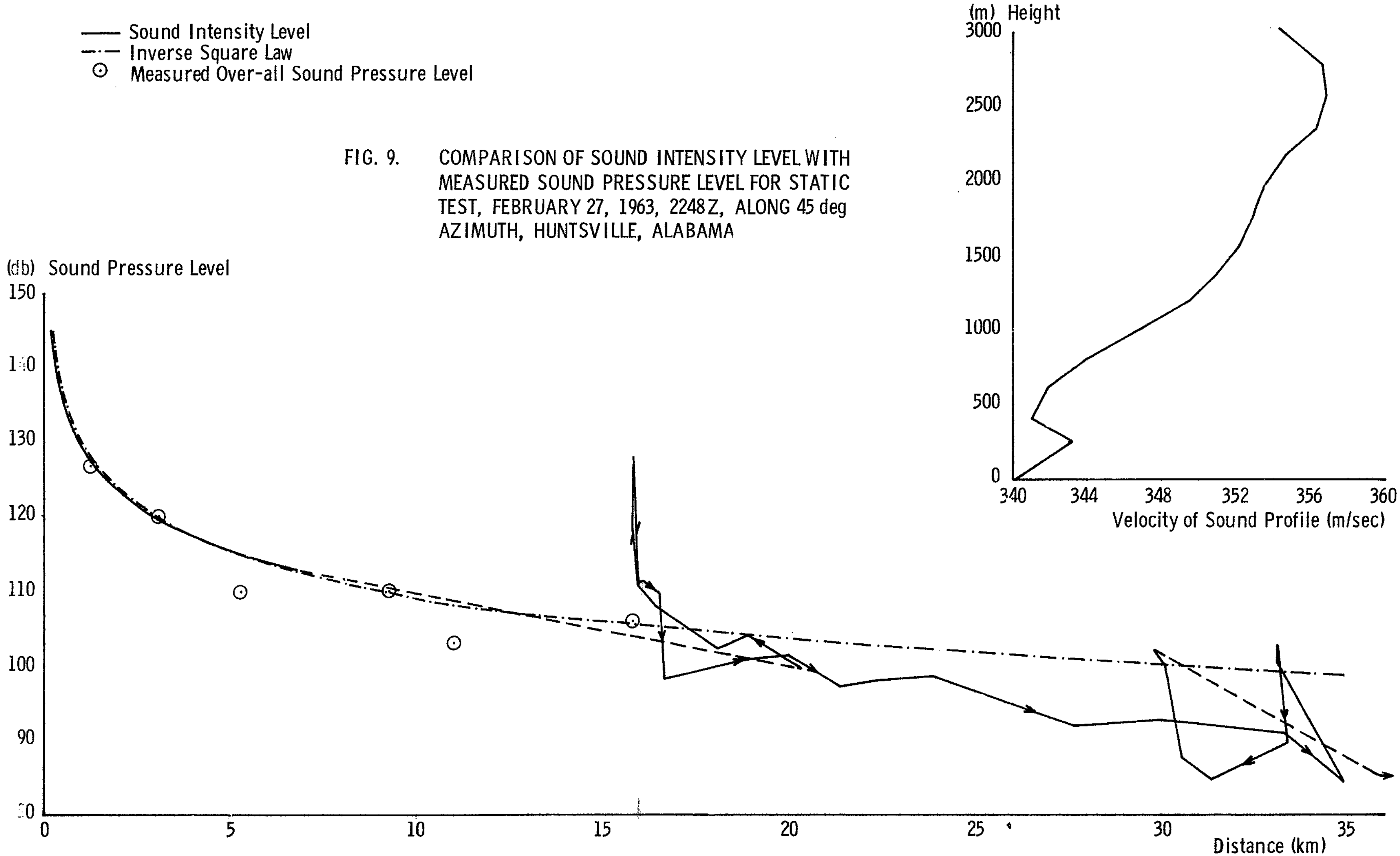


FIG. 9. COMPARISON OF SOUND INTENSITY LEVEL WITH MEASURED SOUND PRESSURE LEVEL FOR STATIC TEST, FEBRUARY 27, 1963, 2248Z, ALONG 45 deg AZIMUTH, HUNTSVILLE, ALABAMA

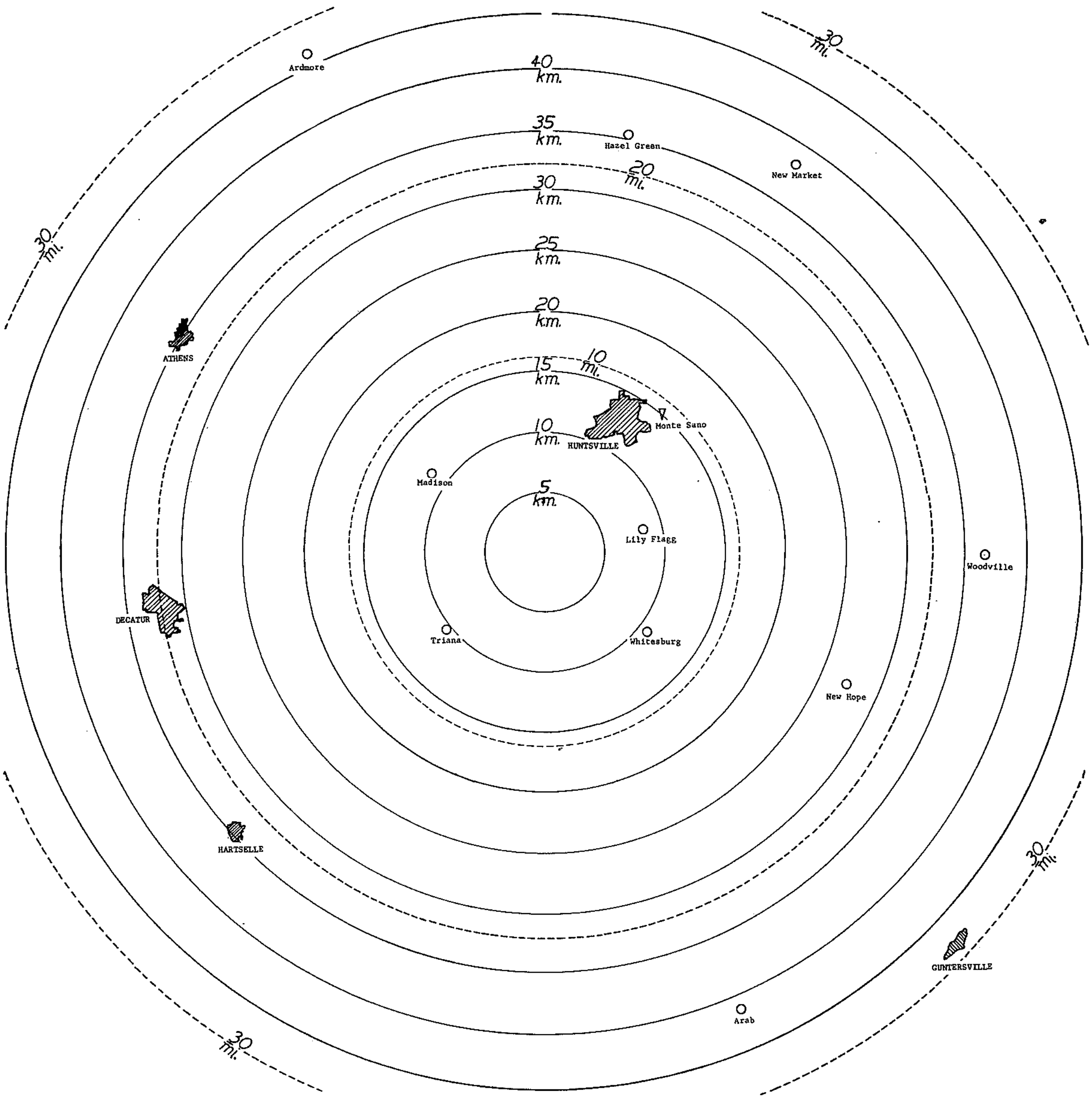


FIG. 10. MAP OF MSFC STATIC TEST AREA

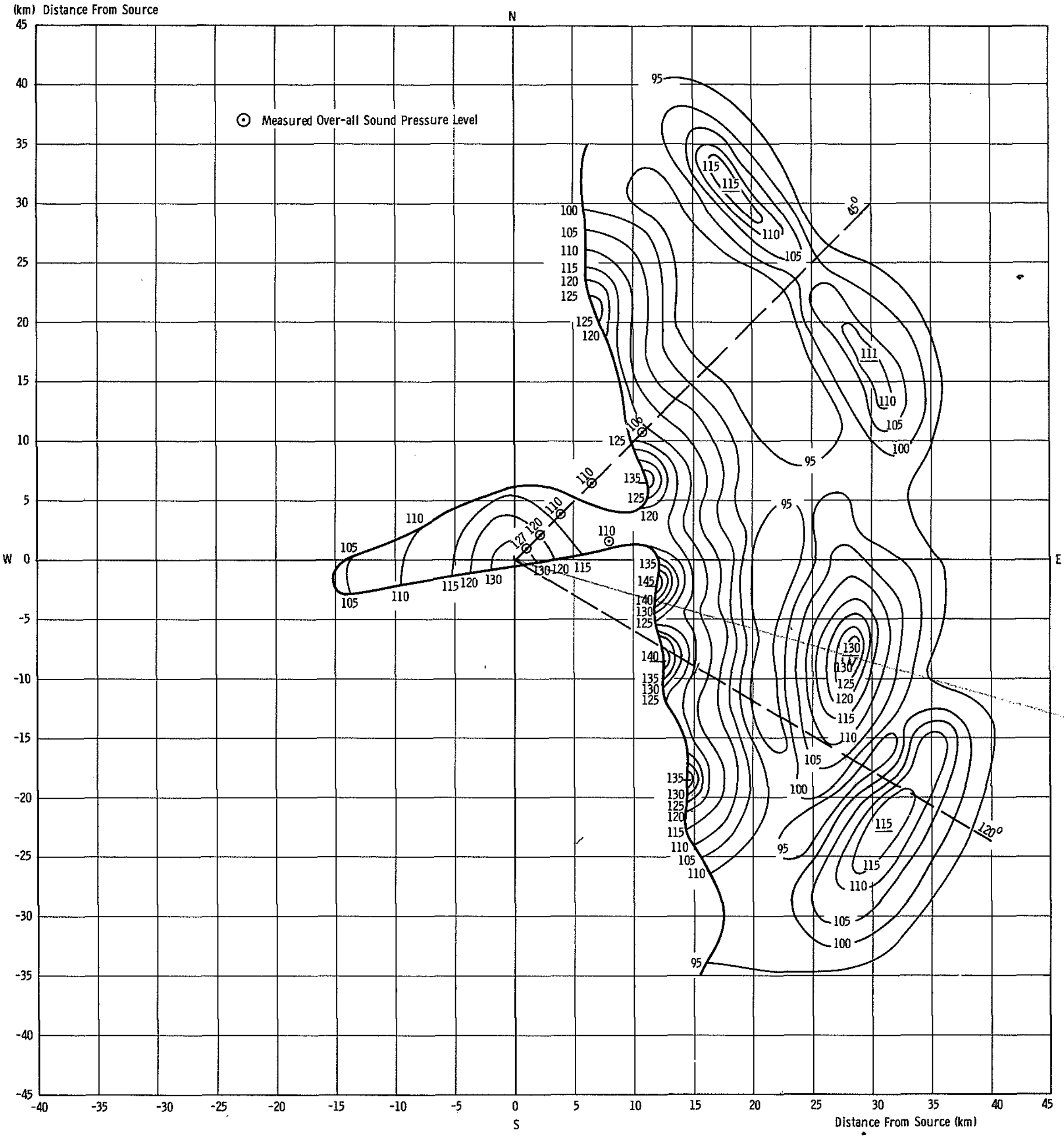


FIG. 11. SOUND INTENSITY LEVELS (db) IN VICINITY OF MSFC STATIC TEST
FEBRUARY 27, 1963, 2248Z

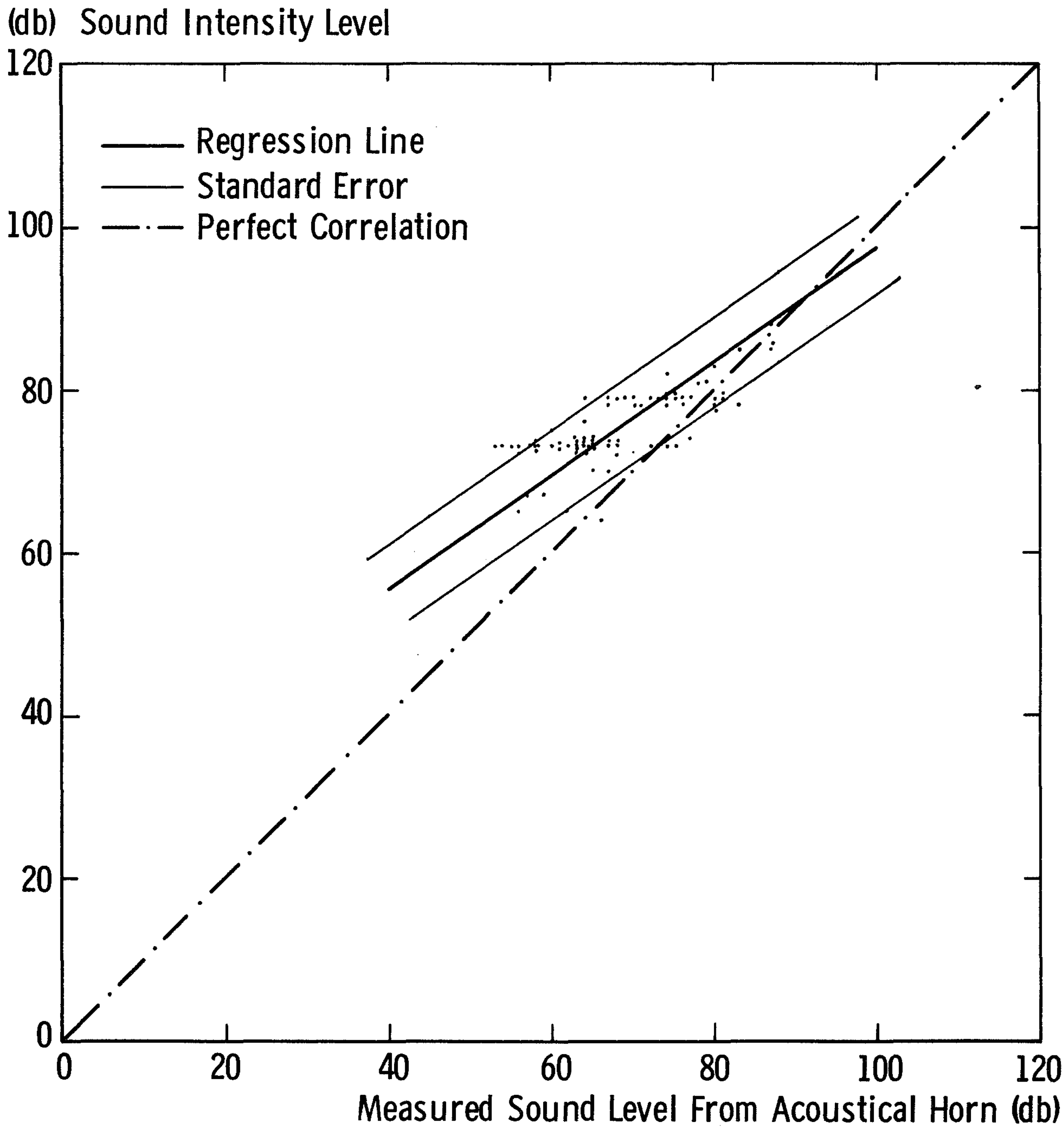


FIG. 12. COMPARISON OF SOUND INTENSITY LEVEL AND MEASURED OVER-ALL SOUND PRESSURE LEVEL FROM ACOUSTICAL HORN FOR CONDITION OF UNIFORM RAYS RETURNING

JANUARY 1963 TO JUNE 1963

NUMBER OF PAIRED VALUES: 83

MISSISSIPPI TEST OPERATIONS

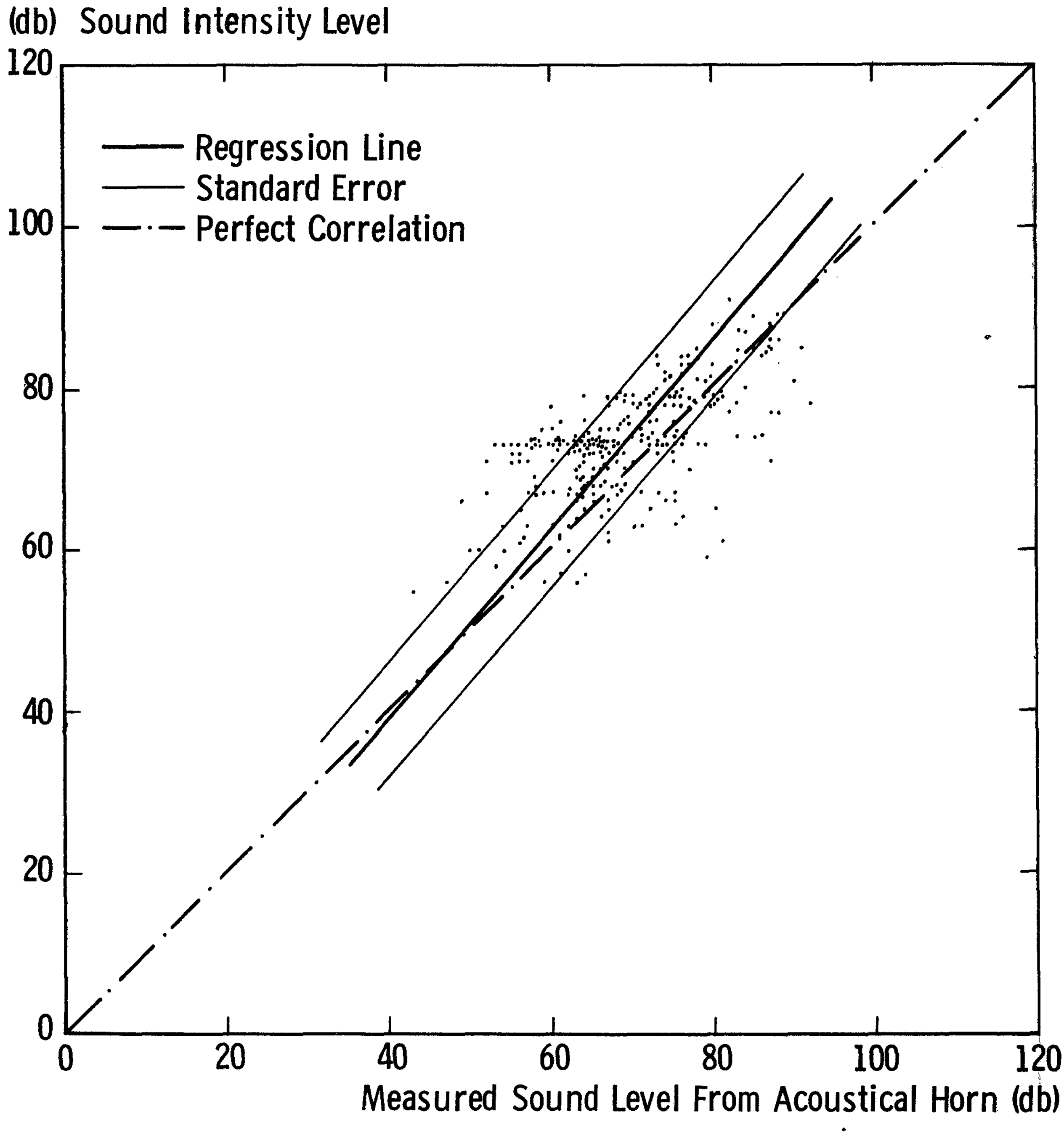


FIG. 13. COMPARISON OF SOUND INTENSITY LEVEL FOR ALL CASES (FOCUSING CONDITIONS AND UNIFORM RAYS RETURNING) WITH MEASURED OVER-ALL SOUND PRESSURE LEVEL FROM ACOUSTICAL HORN

JANUARY 1963 TO JUNE 1963
NUMBER OF PAIRED VALUES: 267
MISSISSIPPI TEST OPERATIONS

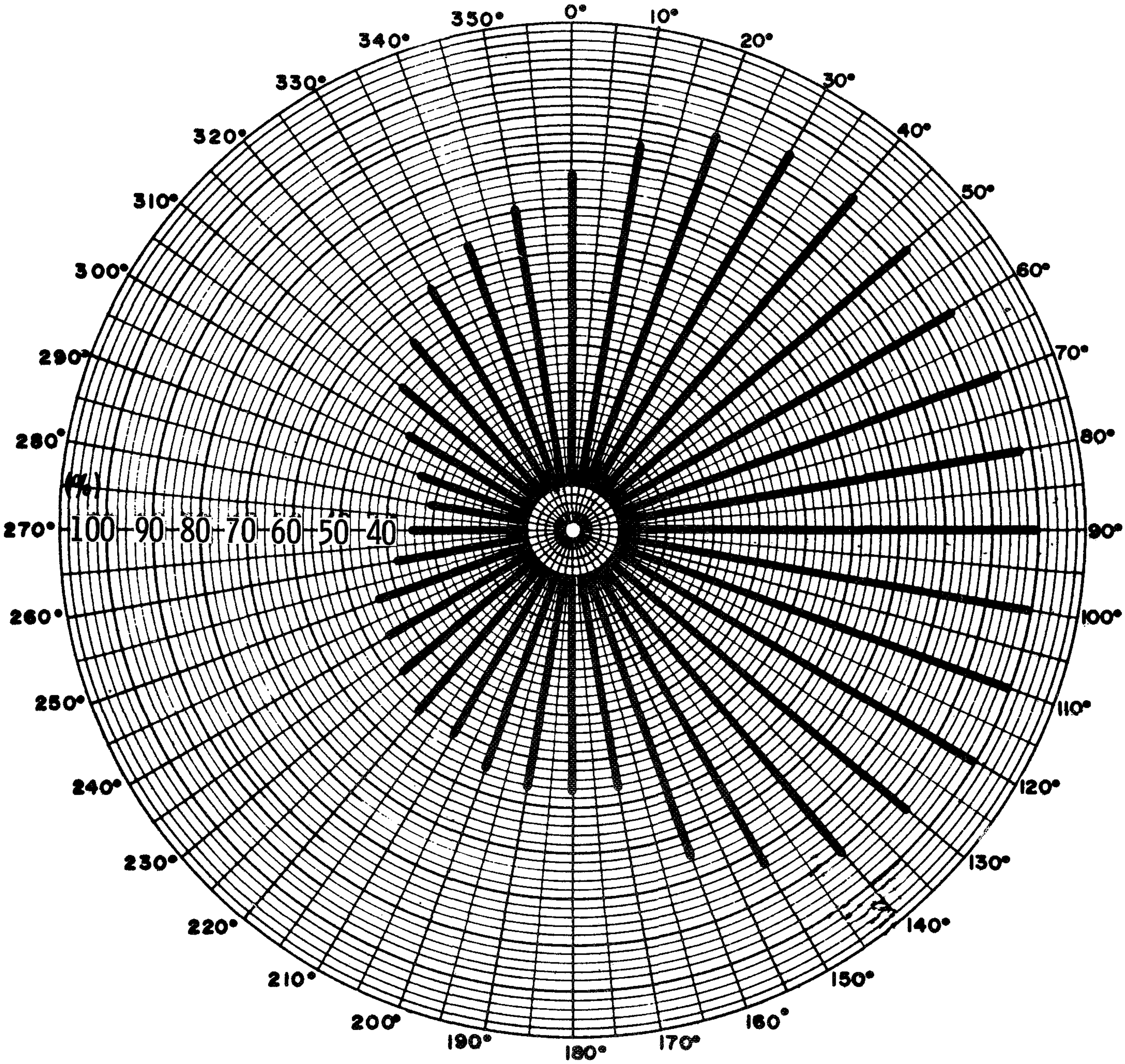


FIG. 14. FREQUENCY OF RAYS RETURNING WITH RESPECT TO AZIMUTHS
JANUARY (1962-1963)
MSFC
HUNTSVILLE, ALABAMA

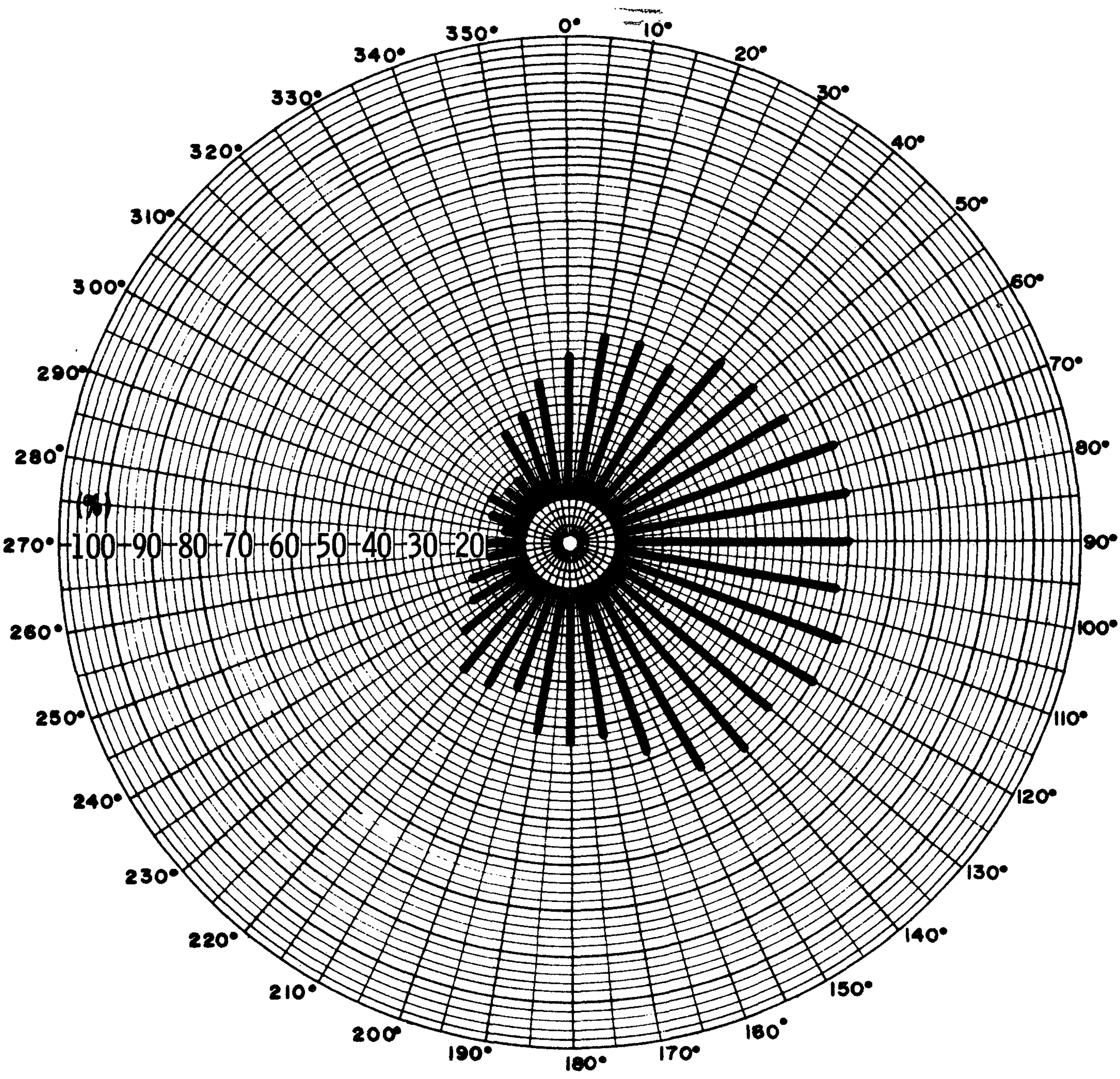


FIG. 15. FREQUENCY OF RAYS RETURNING WITH RESPECT TO AZIMUTHS
JULY (1962-1963)
MSFC
HUNTSVILLE, ALABAMA

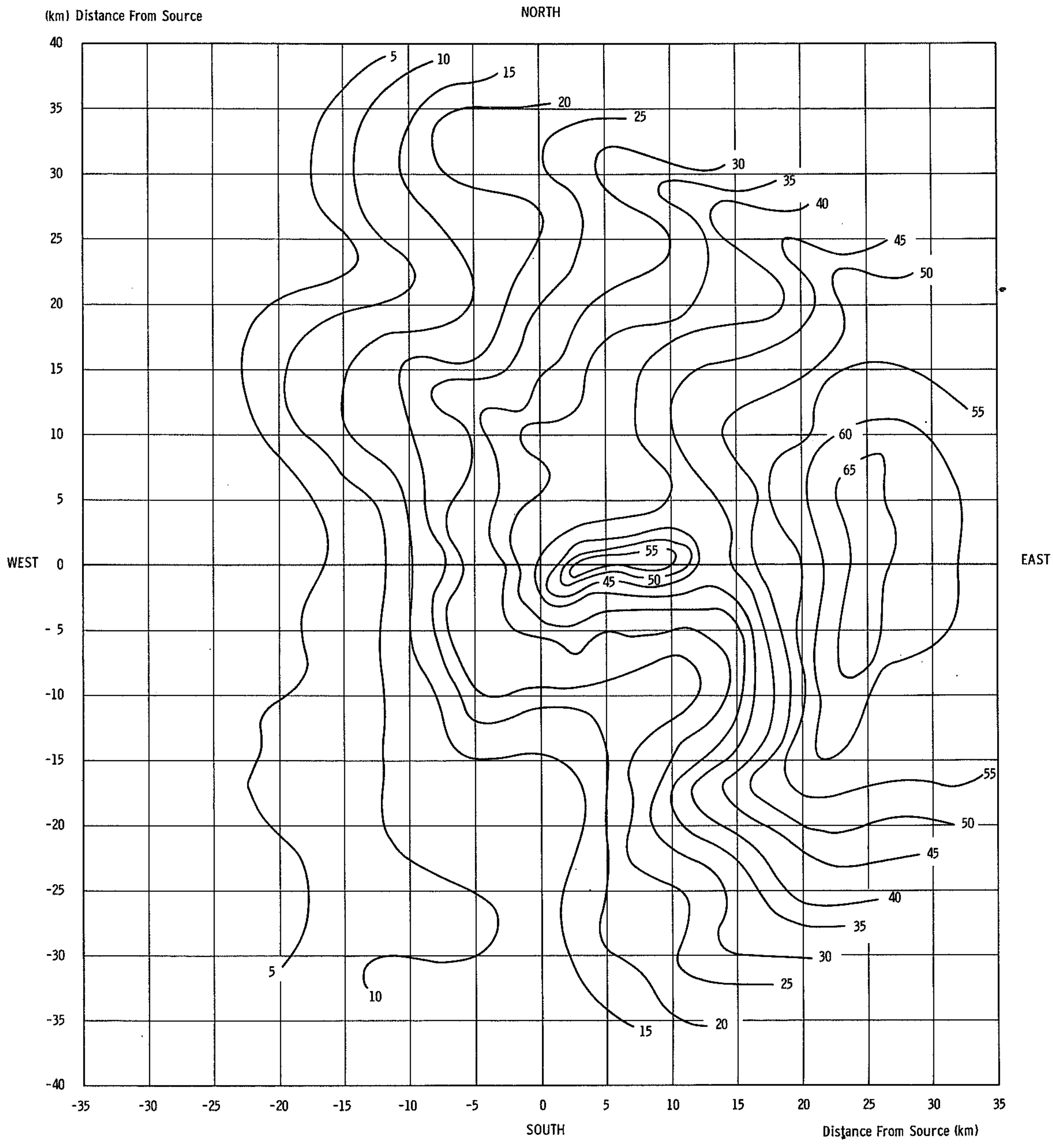


FIG. 16. FREQUENCY (%) OF RAYS RETURNING WITHIN A DEFINED AREA AT 1630 CST

JAN (1962 - 1963)
MSFC
HUNTSVILLE, ALA.

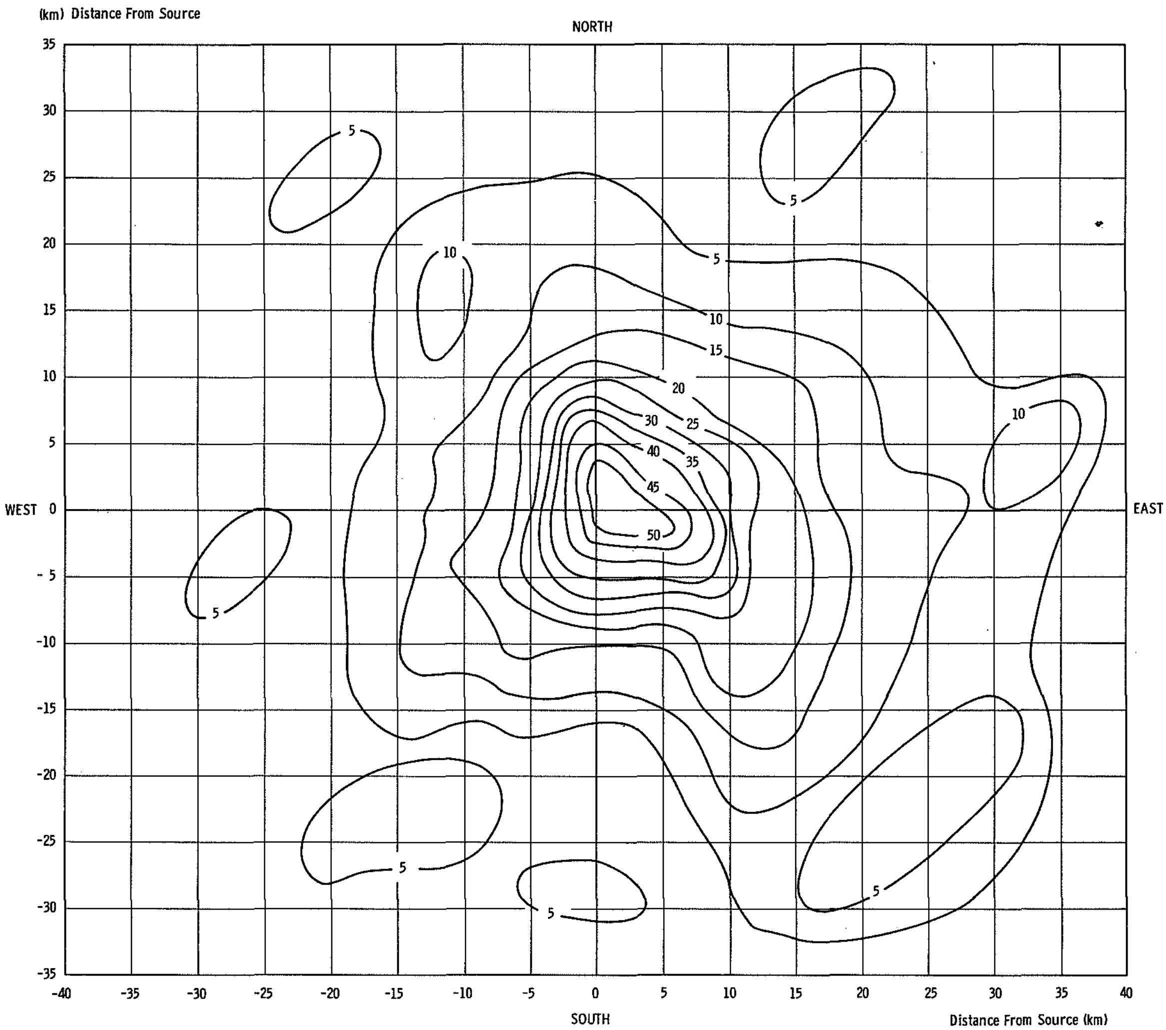


FIG. 17. FREQUENCY (%) OF RAYS RETURNING WITHIN A DEFINED AREA AT 1630 CST

JULY (1962 - 1963)
MSFC
HUNTSVILLE, ALA.

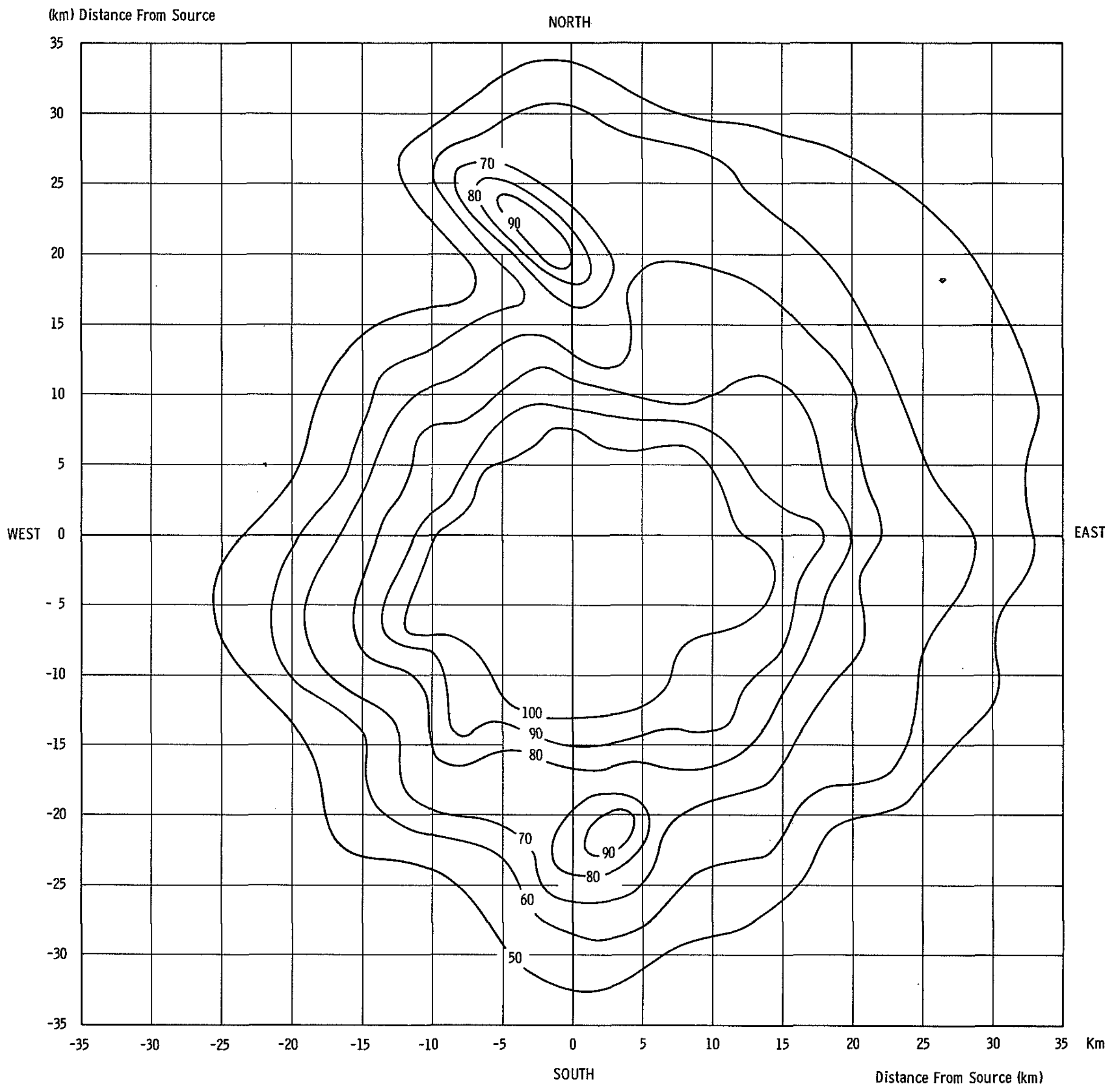


FIG. 18. FREQUENCY (%) OF THE RAYS THAT RETURNED AT 1630 CST WHICH PRODUCED SOUND INTENSITY LEVELS ≥ 110db, FOR SATURN V

JAN (1962 - 1963)

MSFC

HUNTSVILLE, ALA.

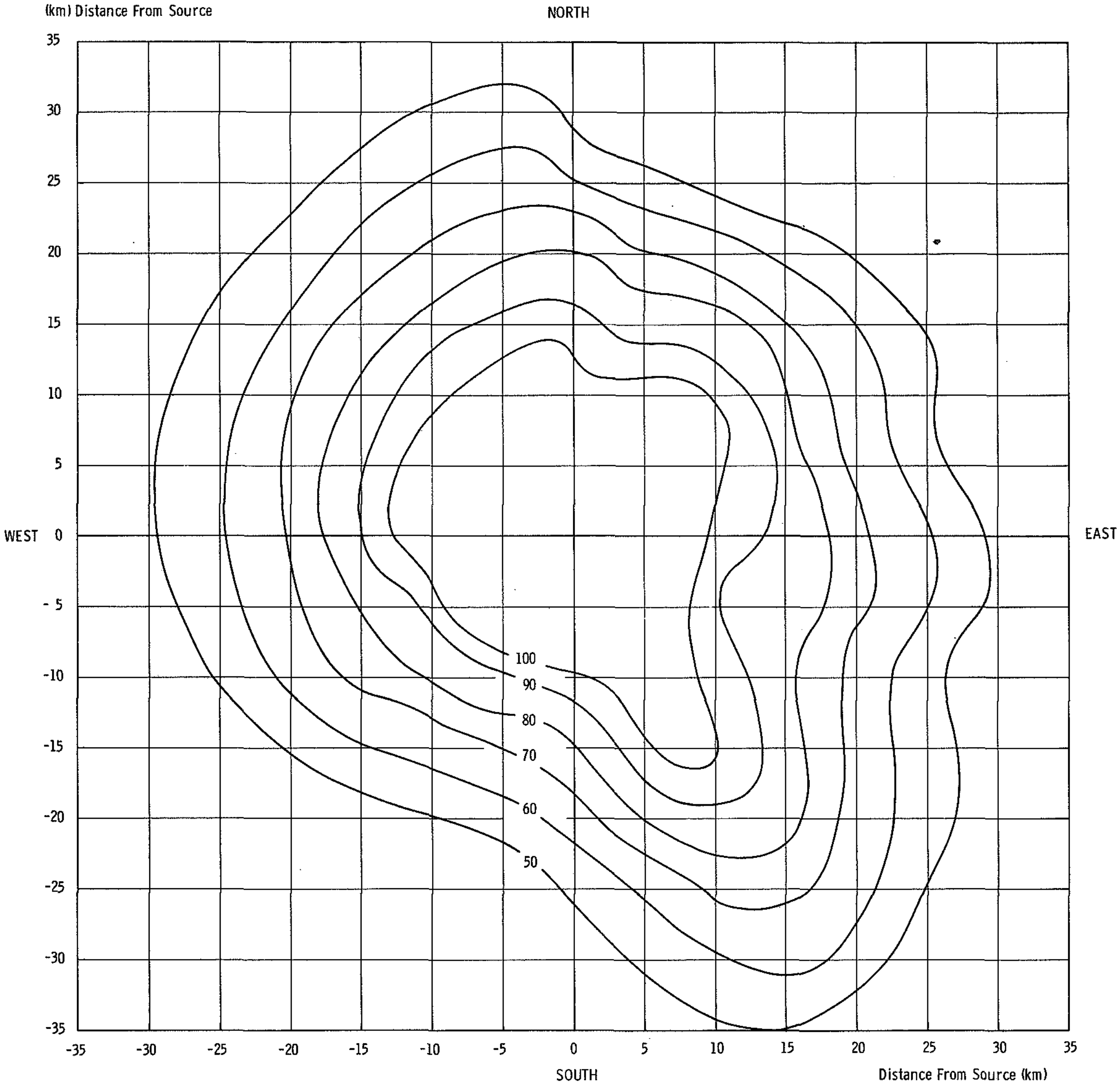


FIG. 19. FREQUENCY (%) OF THE RAYS THAT RETURNED AT 1630 CST WHICH PRODUCED SOUND INTENSITY LEVELS ≥110 db, FOR SATURN V

JULY (1962 - 1963)

MSFC

HUNTSVILLE, ALA.